Spin Identification of the Randall-Sundrum Graviton at the LHC

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Abstract. Using as basic observable an angular-integrated asymmetry to be measured in Drell-Yan lepton-pair production at the LHC, we discuss the identification reach on the spin-2 of the lowest-lying Randall-Sundrum resonance predicted by gravity in one warped extra dimension, against the spin-1 and spin-0 hypotheses. Numerical results indicate that, depending on the graviton coupling strength to the standard model particles, such a spin-2 identification can extend up to mass scales of 1.0–1.6 TeV and 2.4–3.2 TeV for LHC integrated luminosities of 10 and 100 fb^{-1}, respectively.

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INTRODUCTION

Heavy quantum states, with masses $M \gg M_{W,Z}$, are generally predicted by new physics (NP) models. If the masses are in the TeV range, such non-standard objects could be directly revealed as peaks, or resonances, in the cross sections for reactions among standard model (SM) particles at supercolliders.

The *discovery reach* represents the upper limit of the mass range where a peak can be observed experimentally. It depends, among other things, on the collider energy and the expected statistics, and determines an accessible region for the NP model parameters. However, once a peak is observed, the determination of the underlying model against others, potentially giving the same mass and number of events, is needed. Accordingly, for any model, the *identification reach* defines the upper limit of the mass range where the source of the peak can be determined or, equivalently, the competitor models can be excluded for all values of their parameters. Clearly, the identification reach is expected to select a subdomain of the model parameters accessible to discovery.

The resonance spin represents a powerful discriminating observable in this regard. Popular examples of NP scenarios that can produce (narrow) peaks in cross sections with the same mass and number of events, and can be discriminated by a spin analysis are: *i)* Models of gravity in extra spatial dimensions (spin-2); *ii)* Models with heavy neutral gauge bosons Z' (spin-1); and *iii)* SUSY models with R-parity breaking sneutrino couplings (spin-0). Here, we discuss the identification reach on the lowest-lying, spin-2, Randall-Sundrum (RS) graviton resonance [1], against *both* the spin-1 and spin-0 hypotheses, that can be obtained from the experimental study of the inclusive dilepton production process at LHC ($l = e, \mu$):

$$p + p \to l^+ l^- + X. \tag{1}$$

While the total resonant cross section, integrated over the dilepton invariant mass under the peak at $M = M_G$, determines the number of events, hence the discovery reach, for the assessment of the spin-2 identification reach we adopt as basic observable a specific angular-integrated asymmetry, A_{CE}, at $M = M_G$ [2]. The angle is that between the final lepton and the initial quark or gluon in the dilepton center-of-mass frame. This asymmetry has the built-in feature of directly disentangling the spin-1 from other spin hypotheses [3, 4] and, being a ratio of cross sections, should be less affected by systematic uncertainties than other observables. Earlier attempts to discriminate spin-2 from spin-1, based on 'absolute' angular differential distributions, have been presented, *e.g.*, in Refs. [5, 6] and in the experimental Ref. [7].

NEW PHYSICS MODELS

RS model of gravity in extra dimensions

This scenario is a candidate solution to the gauge hierarchy problem, and its simplest version is based on one compactified 'warped' spatial extra dimension and a two-brane setup. The SM particles are localized to the TeV brane, gravity can propagate in the full 5-dimensional bulk and in particular, on the Planck brane, has an effective scale determined by $\overline{M}_{\mathrm{Pl}} = 1/\sqrt{8\pi G_{\mathrm{N}}} = 2.44 \times 10^{18}$ GeV. On the TeV brane the gravity scale Λ_π is suppressed by the exponential 'warp' factor, $\Lambda_\pi = \overline{M}_{\mathrm{Pl}} \exp(-\pi k R_c)$, with $k \sim \overline{M}_{\mathrm{Pl}}$ the 5-dimensional curvature and R_c the compactification radius. Boundary conditions at the branes determine a tower of spin-2 graviton resonances $G^{(n)}$ ($n \geq 1$). Their predicted mass spectrum is $M_n = M_1 x_n/x_1$ with M_1 the lowest resonance mass and x_n the roots of the Bessel function $J_1(x_n) = 0$. Their TeV brane couplings to the SM particles are given by

$$-\mathscr{L}_{\mathrm{TeV}} = \left[\frac{1}{\overline{M}_{\mathrm{Pl}}} G^{(0)}_{\mu\nu}(x) + \frac{1}{\Lambda_\pi} \sum_{n=1}^{\infty} G^{(n)}_{\mu\nu}(x)\right] T^{\mu\nu}(x), \qquad (2)$$

where $T^{\mu\nu}$ is the energy-momentum tensor and $G^{(0)}$ denotes the zero-mode, ordinary, graviton. For $kR_c \simeq 12$, Λ_π as well as the masses M_n (through the relation $M_1 = \Lambda_\pi k x_1/\overline{M}_{\mathrm{Pl}}$) are $\mathscr{O}(\mathrm{TeV})$. This opens up the interesting possibility of observing gravity effects at colliders, in particular to reveal the graviton excitation exchange in the process (1). The contributing, tree level, partonic processes

$$q\bar{q} \to G \to l^+l^- \qquad \text{and} \qquad gg \to G \to l^+l^- \qquad (3)$$

should yield cross-section peaks at the invariant dilepton mass $M = M_n$, with characteristic angular distributions [8].

The RS model thus depends on two independent parameters, that can be chosen as $M_G \equiv M_1$ and the universal 'coupling' $c = k/\overline{M}_{\mathrm{Pl}}$ (in which case Λ_π is a derived parameter). Theoretically 'natural' limits are $0.01 \leq c \leq 0.1$ and $\Lambda_\pi < 10$ TeV [9]. Current 95% C.L. experimental lower limits on M_G, from the Tevatron collider, range from 300 GeV ($c = 0.01$) to 900 GeV ($c = 0.1$) [10]. One should notice that the unevenly spaced spectrum could be distinctive of the model by itself. However, in practice, due to the large masses involved, only the first RS resonance might be accessible at LHC, so that the spin-2 determination should be a necessary test of the RS model.

Heavy neutral gauge bosons

Turning to spin-1 exchanges in the process (1), Z's generally occur in electroweak models based on extended gauge symmetries. The leading-order partonic process, $q\bar{q} \to Z' \to l^+l^-$, should show up as a peak in the dilepton invariant mass distribution at $M = M_{Z'}$ with, in this case, the *same* angular distribution as the SM γ and Z exchanges. Besides the mass $M_{Z'}$, the model parameters are the vector and axial-vector Z' couplings to quarks and leptons. Popular scenarios are the cases where such couplings are specified theoretically: the list includes Z'_χ, Z'_ψ, Z'_η, $Z'_{\rm LR}$, $Z'_{\rm ALR}$ models, and the 'sequential' $Z'_{\rm SSM}$ model with the same couplings as the SM. Details can be found, *e.g.*, in the recent Ref. [11]. It turns out that, at the assumed LHC luminosity, the spin-2 RS resonance can be distinguished from the ALR and SSM spin-1 scenarios already at the level of signal events [2]. For the other Z' models, there are 'confusion regions' in the parameter spaces where spin-2 and spin-1 exchanges give rise to the same peaks and number of events, and therefore can be distinguished by a spin analysis only. Current experimental, model-dependent, lower limits on $M_{Z'}$, from the Tevatron collider, are in the range 500-900 GeV [12].

Sneutrino exchange

In SUSY theories with R-parity breaking, sparticles can be exchanged in the process (1) and appear as peaks in the dilepton invariant mass. This is the case of the spin-0 sneutrino formation by quark-antiquark annihilation, followed by leptonic decay [13]: $q\bar{q} \to \tilde{\nu} \to l^+l^-$. At the peak in the dilepton invariant mass, $M = M_{\tilde{\nu}}$, the spin-0 character implies a flat angular distribution. Basically, the cross section in this model depends on $M_{\tilde{\nu}}$ and on the product $X = (\lambda')^2 B_l$, where λ' is the R-parity breaking sneutrino coupling to $d\bar{d}$ and B_l the sneutrino leptonic branching ratio. Current constraints on X are very loose, and there exists an extended domain where $\tilde{\nu}$ production can mimic RS resonance formation (same mass and number of events under the peak), for details see [2].

$A_{\rm CE}$ ASYMMETRY AND SPIN-2 RS GRAVITON IDENTIFICATION

With $z = \cos\theta_{\rm cm}$ and $R = G, V, S$ denoting the spin-2, spin-1 and spin-0 hypotheses, respectively, we define the evenly integrated center-edge asymmetry:

$$A_{\rm CE}(M_R) = \frac{\sigma_{\rm CE}(R_{ll})}{\sigma(R_{ll})} \quad \text{with} \quad \sigma_{\rm CE}(R_{ll}) \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-z_{\rm cut}}^{-z^*} + \int_{z^*}^{z_{\rm cut}}\right)\right] \frac{{\rm d}\sigma(R_{ll})}{{\rm d}z}\,{\rm d}z. \quad (4)$$

In (4): $0 < z^* < z_{\rm cut}$ is a priori free, and defines the separation between the "center" and the "edge" angular regions; $|z| < z_{\rm cut}$ accounts for detector angular acceptance; cross sections are integrated over the lepton-pair rapidity and over a bin in the lepton-pair invariant mass M centered at the peak $M = M_R$ and with size ΔM appropriate to account for the detector resolution, see, *e.g.*, Ref. [14]. To a very good approximation, the explicit z^* dependencies of $A_{\rm CE}$ are, for the three spin-hypotheses:

$$A_{\rm CE}^G = \varepsilon_q^{\rm SM} A_{\rm CE}^V + \varepsilon_q^G \left[2z^{*5} + \frac{5}{2}z^*(1 - z^{*2}) - 1\right] + \varepsilon_g^G \left[\frac{1}{2}z^*(5 - z^{*4}) - 1\right], \quad (5)$$

$$A_{\rm CE}^{V} \equiv A_{\rm CE}^{\rm SM} = \frac{1}{2}z^*(z^{*2}+3)-1, \quad A_{\rm CE}^{S} = \varepsilon_q^{\rm SM} A_{\rm CE}^{V} + \varepsilon_q^{S}(2z^*-1). \tag{6}$$

In (5), ε_q^G, ε_g^G and $\varepsilon_q^{\rm SM}$ are the fractions of resonant events for $q\bar{q}, gg \to G \to l^+l^-$ and SM background, respectively, with $\varepsilon_q^G + \varepsilon_g^G + \varepsilon_q^{\rm SM} = 1$. They are determined, as functions of M, by the overlaps of parton distribution functions, for which we choose the CTEQ6 ones [15]. Analogous definitions hold for Eq. (6). Strictly, Eqs. (5)-(6) are exact in the limit $z_{\rm cut} = 1$, whereas we will impose $z_{\rm cut} = 0.987$: the difference is numerically negligible at the 'optimal' values $z^* \simeq 0.5$ used in the subsequent analysis. The numerical results presented here are obtained from 'full' calculations with foreseen experimental cuts, such as lepton pseudorapidity $|\eta_l| < 2.5$ and transverse momenta $p_{T,l} > 20\,{\rm GeV}$. Also, a (perhaps optimistic) lepton identification efficiency of 90% has been assumed to evaluate the statistics.

One should notice, in Eq. (6), that $A_{\rm CE}^{V} \equiv A_{\rm CE}^{\rm SM}$ and, therefore, deviations of $A_{\rm CE}$ from the SM predictions definitely signal NP exchanges different from spin-1 models.

We now suppose that a peak is discovered in the dilepton mass distribution for the process (1) at $M = M_R$, and make the hypothesis that it is consistent with a spin-2 RS graviton resonance (in which case, M_R must be identified as M_G). To assess the level at which the spin-1 *and* spin-0 hypotheses can be excluded as competing sources of the peak with the same number of events, hence the spin-2 hypothesis being established, one can consider the deviations:

$$\Delta A_{\rm CE}^{V} = A_{\rm CE}^{G} - A_{\rm CE}^{V} \qquad \text{and} \qquad \Delta A_{\rm CE}^{S} = A_{\rm CE}^{G} - A_{\rm CE}^{S}. \tag{7}$$

As an example, Fig. 7 of Ref. [2] shows $A_{\rm CE}$ *vs* z^* for resonances with different spins, the same mass $M_R = 1.6$ TeV and the same number of events, $c = 0.01$ for the RS exchange, and LHC luminosity $\mathcal{L}_{\rm int} = 100\,{\rm fb}^{-1}$ (left panel). The right panel of that figure shows the corresponding deviations (7). The vertical bars attached to the dot-dashed line representing the RS model, give 2σ statistical uncertainties on the model itself. The figure suggests that, indeed, at the assumed LHC luminosity, the spin-2 RS graviton with $M_G = 1.6$ TeV and $c = 0.01$ can be discriminated from the other spin hypotheses by means of $A_{\rm CE}$ at $z^* \simeq 0.5$.

One can systematically generalize this example, and look at the domain in the RS parameter plane (M_G, c) where a peak can be *identified* as originating from spin-2 RS exchange, with the spin-1 and spin-0 hypotheses excluded. This domain will represent the searched for *identification reach* on the RS graviton resonance. For this purpose, one can adopt a simple-minded χ^2 criterion, where the χ^2 functions are defined as $\chi^2 = [\Delta A_{\rm CE}/\delta A_{\rm CE}]^2$, with $\Delta A_{\rm CE}$ given in (7), and $\delta A_{\rm CE}$ the corresponding expected statistical uncertainty pertaining to the RS model. The conditions $\chi^2 > \chi^2_{\rm C.L.}$ determine the ranges in (M_G, c) where the spin-0 and spin-1 hypotheses can be excluded to a given confidence level. The maximum sensitivity of $A_{\rm CE}$ to the spin-2 RS resonance parameters is generally achieved for $z^* = 0.5$.

Figure 1 shows the resulting allowed domain in the RS parameter plane for the spin-2 discrimination at 95% C.L. *vs.* the allowed domain for discovery at 5σ, for two values of LHC integrated luminosity, and the channels $l = e, \mu$ combined [2]. Theoretically suggested bounds on c and Λ_π are taken into account. The meaning of the lines in the two panels are as follows: the lowest RS resonance can be discovered if its representative

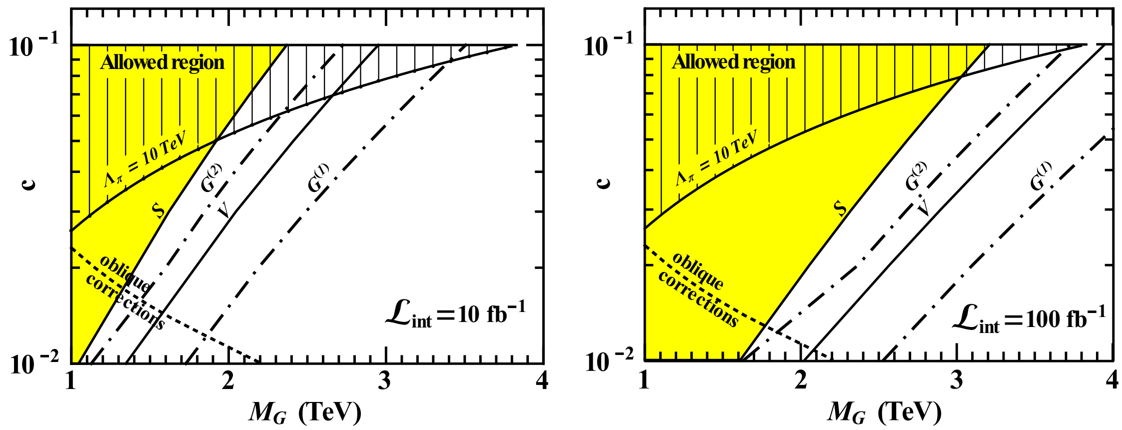

FIGURE 1. Discovery and Identification ranges as defined in the text.

point (M_G, c) lies to the left of the line "$G^{(1)}$"; in the region to the left of curve "V", of course included in the preceding one, the RS resonance spin-1 can be excluded, whereas the spin-0 hypothesis is still open; finally, if the observed resonance has the representative point in the domain to the left of the line "S", also the spin-0 hypothesis can be excluded. Accordingly, this is assumed to represent the searched for domain allowing spin-2 identification. Of course, these statements should be understood in a statistical sense, as specified by the confidence level.

As regards the mass ranges for discovery and identification of the RS graviton resonance, the results in Fig. 1 can be summarized as in Tab. 1. One should notice that, in Fig. 1, the line "S" always lies to the left of the line "V". This reflects the (general) fact that, as seen from Eqs. (5)–(7), $\Delta A_{\rm CE}^{V} > \Delta A_{\rm CE}^{S}$ for all z^*. Thus, if one were able to exclude spin-0, the exclusion of the whole class of spin-1 models would be automatically implied in a model-independent way. Conversely, the request of excluding the spin-0 hypothesis substantially reduces the extension of the parameter domain allowed by the weaker condition of only discriminating spin-2 from spin-1.

The somewhat 'low' values of M_G allowed to spin-0 exclusion suggest to look at the possibility of discovering the next RS resonance, $G^{(2)}$, in addition to $G \equiv G^{(1)}$, recalling that the ratio of masses is in the model a predicted number, $M_G/M^{(2)} = x_1/x_2$. Indeed, such 5σ discovery of $G^{(2)}$ turns out to be possible, with $\mathscr{L}_{\rm int} = 10\,{\rm fb}^{-1}$ for $M_G < 1.1\,$TeV (2.7 TeV) at $c = 0.01$ ($c = 0.1$) and, with $\mathscr{L}_{\rm int} = 100\,{\rm fb}^{-1}$, for $M_G < 1.6$ TeV (3.7 TeV) at $c = 0.01$ ($c = 0.1$). Correspondingly, for a lowest resonance G in the (M_G, c) domain to the left of the line "$G^{(2)}$" in Fig. 1, also the higher graviton excitation with $n = 2$ can be discovered. One can see, therefore, that to the left of the line "S" the spin-2 of the lowest-lying RS resonance can be established and, in addition, also the characteristic RS mass spectrum can be tested by the discovery of the higher resonance, so that the model would be doubly clinched.

One can notice from Fig. 1 the dramatic role in RS graviton searches of the bound $\Lambda_\pi \leq 10\,$TeV, theoretically motivated by the need of not creating additional hierarchies in the model: taken literally, it would imply that, at the high luminosity of 100 fb^{-1}, the mass spectrum test should be feasible in the full discovery domain. However, in practice,

TABLE 1. Discovery and Identification reach [TeV]

	Discovery		Identification	
$\mathscr{L}_{\text{int}}$	$c = 0.01$	$c = 0.1$	$c = 0.01$	$c = 0.1$
10 fb^{-1}	1.7 TeV	3.5 TeV	1.1 TeV	2.4 TeV
100 fb^{-1}	2.5 TeV	4.6 TeV	1.6 TeV	3.2 TeV

such bound should be considered in a qualitative sense, as is the case for the indicative limits from the fit to oblique parameters, taken from [9, 16].

We may conclude by mentioning, as another RS resonance selective process, the inclusive diphoton production $p + p \to G \to \gamma\gamma + X$. Indeed, spin-1 could be excluded directly by $V \not\to \gamma\gamma$, leaving only the spin-2 and spin-0 hypotheses, and the RS model could be strongly tested by measurement of the ratio $Br(G \to \gamma\gamma)/Br(G \to l^+l^-)$ [17]. Currently, only the diphoton invariant mass distribution has been studied experimentally, but angular analysis should be possible, as mentioned in Refs. [5], notwithstanding the dominance of the partonic process $gg \to G \to \gamma\gamma$, strongly peaked near $z = \pm 1$ and potentially affected by the initial bremsstrahlung background. It could be interesting to attempt the application of the asymmetry A_{CE} to this process also.

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